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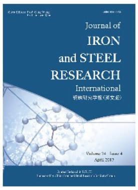

Extracting compressive stress-strain curve based on stick-slip shear banding process in bulk metallic glasses

Jing Hu[1], Yun-xuan Weng[1], Xiao-li Li[1], Bao-an Sun[2,*]

[1] School of Material and Mechanical Engineering, Beijing Technology and Business University, Beijing 100048, China

[2] Herbert Gleiter Institute of Nanoscience, Nanjing University of Science & Technology, Nanjing 210094, Jiangsu, China

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ABSTRACT

Based on the stick-slip process, an effective method to extract the stress-strain curve directly from the crosshead displacement-load raw data in compression of bulk metallic glasses was proposed. The method was tested in two bulk metallic glass samples with different plasticities and shear band morphologies. The extracted stress-strain curves were found to well resemble the stress-strain curve measured by a laser extensometer. In addition, the extracted curve could resolve fine structures of serrated flow much better than that measured by extensometer, thus facilitating the study of shear banding process. Results obtained by this method made the stick-slip dynamics of shear banding valid, and this method could be employed to obtain the real strain of small-sized metallic glass samples where extensometer cannot be applied.

1. Introduction

As a class of amorphous materials, bulk metallic glasses (BMGs), which possess disordered atomic structures and attractive properties, have absorbed considerable interests over past decades[1-3]. Compared with their crystalline counterparts, superior mechanical properties of BMGs such as high strength, large elastic limit and excellent wear resistance also attract many attentions currently[4-6]. However, the plastic deformation of BMGs is highly localized into nanoscale shear bands[7], which is prone to strain softening and unstable[8,9]. This often leads to the catastrophic failure and the poor ductility of BMGs. In general, most of BMGs usually display zero tensile ductility[10], while under compression, some BMGs could manifest some plasticity before the final fracture[11,12]. Therefore, compression test is a common method to investigate the plastic flow and shear banding behavior of BMGs. However, even for compression, recent studies have showed that the shear stability of BMGs has strong size dependence[13,14]. Large and stable plasticity are often achieved in small sized samples. In contrast, plastic BMGs even become completely brittle when the sample size is large (typically exceed 5 mm in diameter with an aspect ratio of 2 ∶ 1). In order to investigate the plastic flow and shear banding process, compression tests are often performed with small size BMG samples with a typical diameter less than 3 mm[15-17]. In such cases, a precise measurement on the strain of samples becomes a hard issue since the extensometer is difficult to be mounted in small size samples.

Once initiated, a shear band often proceeds in a stick-slip manner, which is manifested as serrated flow behavior in stress-strain *vs*. time curves[8,18,19]. Typical serrations are characterized by the repeated cycles of a sudden stress drop or flow event followed by a slow elastic reloading[20]. Thus, serrated flow actually reflects the intermittent process of plastic flow in BMGs[21,22]. On one hand, this behavior complicates the understanding on the plastic flow mechanism in BMGs; on the other hand, it provides a unique opportunity for characterization of the dynamics of highly localized shear bands[23]. In this way, the shear band velocity[24,25], viscosity[21] and temperature rise[24] etc., have been directly or indirectly measured during the propagation process. It shows that the real strain of samples can be precisely extracted from the crosshead displacement during compression through the stick-slip shear banding process. Thus, the compressive stress-strain curve can be constructed directly from the crosshead displacement and load raw data without the extensom-

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* Corresponding author. Prof., Ph.D.

E-mail address: *baoansun@njust.edu.cn* (*B. A. Sun*).

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eter. The method has been tested and verified in two BMG samples with distinct plasticity and shear band morphologies. The method is particularly useful to obtain the strain of small size BMGs where the extensometer cannot be applied.

2. Theoretical Method

The deformation process of a BMG sample under compression is schematically shown in Fig. 1. The sample-machine system[20] is loaded at a constant external rate v_0. Once the loading stress reaches the yield strength of BMG, a shear band will form and subsequently proceed in a stick-slip manner along a shear plane. In the stick phase, the shear band velocity $v \ll v_0$, and thus the deformation can be regarded as elastic in nature; while in the slip phase, $v \gg v_0$ and a sudden plastic event occurs[21,26]. From this sense, the elastic deformation part and the plastic flow part can be regarded to appear alternatively during the stick-slip deformation process. The real displacement or strain of the sample in each part can be extracted separately. In the stick part, the applied crosshead displacement Δx^{e} is accommodated by the elastic deformation of the sample-machine system:

$$\Delta x^{\mathrm{e}} = \Delta x_{\mathrm{S}}^{\mathrm{e}} + \Delta x_{\mathrm{M}}^{\mathrm{e}} \tag{1}$$

where, $\Delta x_{\mathrm{S}}^{\mathrm{e}}$ and $\Delta x_{\mathrm{M}}^{\mathrm{e}}$ are the elastic deformation displacement of the sample and machine, respectively. As the sample and machine are in series, there should have $\kappa_{\mathrm{M}} \Delta x_{\mathrm{M}}^{\mathrm{e}} = \kappa_{\mathrm{S}} \Delta x_{\mathrm{S}}^{\mathrm{e}}$ with κ_{M} and κ_{S} being the machine stiffness and sample stiffness, respectively. Substituting this relation into Eq. (1), the elastic displacement of the sample can be obtained:

$$\Delta x_{\mathrm{S}}^{\mathrm{e}} = \frac{\Delta x^{\mathrm{e}} \kappa_{\mathrm{M}}}{\kappa_{\mathrm{M}} + \kappa_{\mathrm{S}}} = \frac{\Delta x^{\mathrm{e}}}{1+S} \tag{2}$$

$$S = \kappa_{\mathrm{S}} / \kappa_{\mathrm{M}} = \pi d^2 E / (4 L \kappa_{\mathrm{M}}) \tag{3}$$

where, S is a parameter that can be obtained by Eq. (3); and E, d and L are Young's modulus, diameter and height of the sample, respectively[14,27]. For the slip part, the sliding of shear band will cause the release of elastic energy of the system and thus a sudden stress drop will occur. The stress drop magnitude $\Delta\sigma$ and the vertical shear-band sliding displacement (or the plastic displacement of sample) $\Delta x_{\mathrm{S}}^{\mathrm{p}}$ have the following relation[25]:

$$-\Delta\sigma = k(v_0 \Delta t_{\mathrm{p}} - \Delta x_{\mathrm{S}}^{\mathrm{p}}) \tag{4}$$

where k is the elastic constant of the system, which can be defined as $k = E/L(1+S)$[20]; and Δt_{p} is the slip duration for the stress drop. From Eq. (4), it can be obtained:

$$\Delta x_{\mathrm{S}}^{\mathrm{p}} = v_0 \Delta t_{\mathrm{p}} + \Delta\sigma / k \tag{5}$$

According to Eqs. (2) and (5), the real elastic and plastic sample strain for each elastic loading part and the load drop part can be extracted respectively, throughout the whole crosshead displacement-load curve. Thus, the real strain-stress curve of sample can be constructed without applying the extensometer in principle.

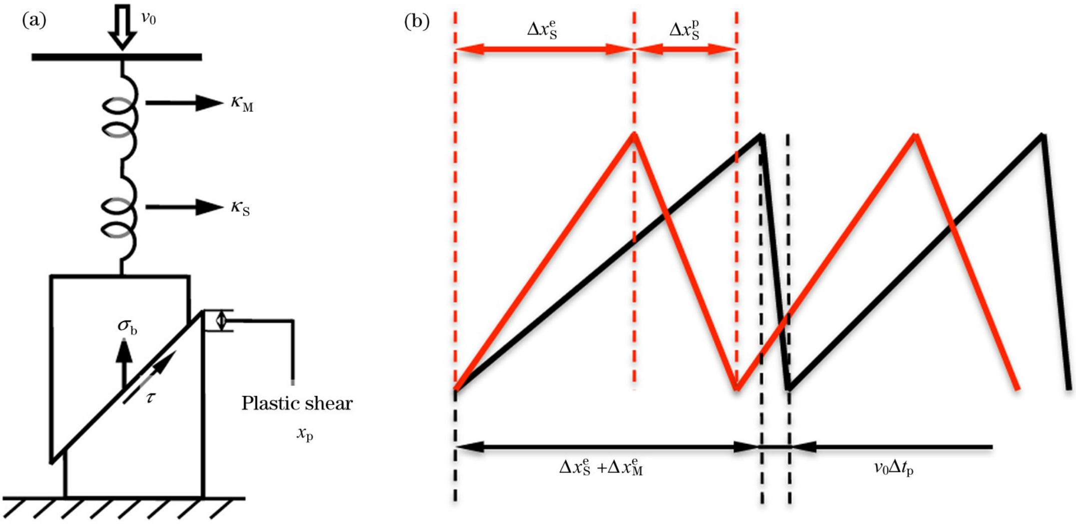

Fig. 1. Schematic illustration of machine-sample system during compression (a), and stick-slip deformation process of BMGs (b).

3. Results and Discussion

BMG alloy ingots with nominal composition of $Zr_{65}Cu_{15}Ni_{10}Al_{10}$ were prepared by the arc melting of mixtures of pure elements in a Ti-gettered argon atmosphere, and were sucked into a copper mould. Different compressive plasticity values were displayed with different sample sizes. Glassy rods with diameters of 1 and 2 mm and lengths of 20−50 mm were obtained. The amorphous nature of samples was examined by X-ray diffraction (XRD, PANalytical X′ Pert PRO) with Co-Kα radiation and differential scanning calorimetry (DSC, Perkin Elmer DSC7). The Young′s modulus of the BMG was measured by acoustic pulse echo overlap method with a MATEC